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Original Article

KU2EPA-Balances: A software to compute water, energy and chlorine mass balances in water distribution networks♣

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Abstract

This paper presents KU2EPA-Balances, a Python-based software to analyze water distribution networks (WDNs). The software calculates water, energy, and chlorine mass balances in WDNs and hence the losses of all three quantities. Such losses can be seen as network performance indicators. Specifically, KU2EPA-Balances is the first software that computes chlorine mass balance. The software requires the same type of network input file as the EPANET software. Energy loss is divided into two components: energy dissipation and energy outgoing through leaks. Similarly, chlorine mass loss is divided into mass decay due to chemical reactions and mass outgoing through leaks. KU2EPA-Balances provides comprehensive hourly and daily results, enabling short-term audits. The software also features a graphical user interface (GUI) and generates output summary graphs to facilitate user interaction. Researchers and practitioners can utilize this software to analyze the nature of WDNs, and devise strategies for loss control intended to enhance system efficiency.

Keywords: water balance, energy balance, chlorine mass balance, water distribution network, EPANET

1. Introduction

A potable water supply system can be divided into four main works: raw water collection work, purification work, transmission work, and distribution work. Among these works, a water distribution network (WDN) plays a critical role in conveying potable water from its sources to various end-users, serving residential, commercial, industrial and firefighting purposes. Typically, a WDN constitutes the largest portion in terms of size and pipe length and is the most complex system to manage. In a WDN, three primary types of losses can occur: water loss, energy loss, and water quality deterioration. To control and mitigate these losses, the audit method that classifies each component in the balance has proven to be an effective tool for identifying the components responsible for the losses, calculating the performance, and benchmarking against other water utilities.

The water audit method was introduced by the International Water Association (IWA) to classify all water volume inputs, outputs, and losses in a WDN in the accountable water balance (Alegre *et al.* 2006). The IWA water balance is globally recognized as the best practice for assessing water losses and has been adopted and extended by the American Water Works Association (AWWA 2016). The water balance approach allows for the calculation of performance indicators, which are used for benchmarking, performance comparison, and setting performance targets (Wu *et al.* 2011).

Similar to the concept of water balance, the energy balance focuses on energy inputs, outputs, and losses in a WDN. The International Energy Agency (IEA, 2016) estimated that the water sector consumed 4% of the world's total electricity in 2014, with projections indicating an 80% increase by 2040. According to the World Bank (2012), electricity costs account for 5% to 30% of the total operating expenses for water and wastewater utilities worldwide. Cabrera *et al.* (2010) introduced the concept of an energy audit in WDNs, focusing on energy consumption components, especially those associated with leakages. Mamade *et al.* (2015) added new components of energy consumption such as valves, pumps, and

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turbines into the energy balance. Several real-world case studies have evaluated energy losses due to leakage (Dziedzic & Karney 2015; Lapprasert *et al.* 2018; Lenzi *et al.* 2013; Lipiwattanakarn *et al.* 2019, 2021a). Additionally, Pardoa *et al.* (2019) developed a MATLAB-based energy balance software capable of evaluating energy losses due to friction and leakage. Chlorine loss presents a critical concern for water quality in WDNs. The World Health Organization (WHO, 2011) has established a minimum free residual chlorine requirement of 0.2 mg/l for ensuring the safe use of potable water. A pioneering concept of the chlorine mass balance was introduced by Lipiwattanakarn *et al.* (2021b) to assess chlorine losses in WDNs. The chlorine mass outputs are divided into three components: mass delivered to users, outgoing mass through water losses, and mass losses due to chemical reactions, following the same concepts of water and energy balances. In a recent study, Wongpeerak *et al.* (2023) introduced straightforward equations for assessing chlorine mass losses based on a simple theoretical analysis.

EPANET software (Rossman, 2000) is renowned for its capabilities to simulate WDNs. However, it currently lacks the functionality to assess water, energy, and chlorine mass balances. Manually analyzing these three balances in complex WDNs can be troublesome and prone to errors due to the system's intricacy. Therefore, we have developed the first software, KU2EPA-Balances, capable of conducting comprehensive analyses of all three balances. This software, built on the Python programming language, utilizes the Water Network Tool for Resilience (WNTR) (Klise *et al.*, 2017), compatible with EPANET, to provide precise results to users.

2. Balance Calculations

The calculations can be divided into three sections, corresponding to the three types of balances as follows.

2.1 Water balance calculation

Figure 1 shows the water balance components for WDNs in this study. On the input side, the system input volume (W_{IN}) represents the total water volume entering a WDN and can come from reservoirs ($W_{IN,RES}$), tanks ($W_{IN,TANK}$), and junctions ($W_{IN,JUNC}$). The output side comprises two primary components: water outgoing through nodes (W_{OUT}) and water loss (W_{LOSS}). W_{OUT} can be further categorized into water delivered to users ($W_{OUT,USER}$), water outgoing to reservoirs ($W_{OUT,RES}$), and water outgoing to tanks ($W_{OUT,TANK}$). In this study, W_{LOSS} represents the cumulative leakage flow, which is pressure-dependent.

<table>
<tr><td rowspan="4">System input volume
W_{IN}</td><td>Input water from reservoirs
$W_{IN,RES}$</td><td rowspan="3">Water outgoing through nodes
W_{OUT}</td><td>Water delivered to users
$W_{OUT,USER}$</td></tr>
<tr><td>Input water from tanks
$W_{IN,TANK}$</td><td>Water outgoing to reservoirs
$W_{OUT,RES}$</td></tr>
<tr><td rowspan="2">Input water from junctions
$W_{IN,JUNC}$</td><td>Water outgoing to tanks
$W_{OUT,TANK}$</td></tr>
<tr><td colspan="2">Water loss
W_{WL}</td></tr>
</table>

Figure 1. Water balance components

For a defined period, each component can be calculated using the results from the network simulation model, as follows:

$$W_{IN,TYPE} = \sum_{i_t=1}^{n_t} \sum_{i_{I,TYPE}=1}^{n_{I,TYPE}} Q_{i_{I,TYPE},i_t}(t)\Delta t \tag{1}$$

$$W_{OUT,TYPE} = \sum_{i_t=1}^{n_t} \sum_{i_{O,TYPE}=1}^{n_{O,TYPE}} Q_{i_{O,TYPE},i_t}(t)\Delta t \tag{2}$$

$$W_{WL} = \sum_{i_t=1}^{n_t} \sum_{i_{WL}=1}^{n_{WL}} q_{i_{WL},i_t}(t)\Delta t \tag{3}$$

$$q_{WL,i_t} = c_{i_{WL},i_t} \cdot P_{i_{WL},i_t}^{N_1} \tag{4}$$

where Q represents the discharge at a node, t denotes time, and Δt stands for the time interval. i and n are defined as an index and the total count of an index, respectively. The subscripts of i and n are t, I, O, $TYPE$, and WL, denoting time, input, output, type of node, and water loss, respectively. Thus, $TYPE$ can be RES, $TANK$, and $JUNC$, defined as reservoirs, tanks, and junctions, respectively. Furthermore, q is the leak discharge at each junction calculated by the emitter function relating with pressure (P), while c and N_1 are the emitter coefficient and exponent, respectively.

2.2 Energy balance calculation

The energy balance components, as illustrated in Figure 2, provide details about the input, output, and loss side of energy in a WDN. On the input side, the system input energy (E_{IN}) represents the total energy entering a WDN and can come from reservoirs ($E_{IN,RES}$), tanks ($E_{IN,TANK}$), and junctions ($E_{IN,JUNC}$). The output side comprises two primary components: energy outgoing through nodes (E_{OUT}) and energy outgoing through water loss (E_{WL}). On the loss side, the term for the energy dissipated (E_{LOSS}) represents the cumulative energy losses in a WDN, stemming from friction in pipes ($E_{LOSS,PIPE}$) and valves ($E_{LOSS,VALVE}$).

<table>
<tr><td rowspan="7">System input energy
E_{IN}</td><td rowspan="2">Input energy by reservoirs
$E_{IN,RES}$</td><td rowspan="3">Energy outgoing through nodes
E_{OUT}</td><td>Energy delivered to users
$E_{OUT,USER}$</td></tr>
<tr><td>Energy outgoing to reservoirs
$E_{OUT,RES}$</td></tr>
<tr><td rowspan="2">Input energy by tanks
$E_{IN,TANK}$</td><td>Energy outgoing to tanks
$E_{OUT,TANK}$</td></tr>
<tr><td rowspan="2">Energy dissipated
E_{LOSS}</td><td>Energy loss by pipe friction
$E_{LOSS,PIPE}$</td></tr>
<tr><td rowspan="2">Input energy by junctions
$E_{IN,JUNC}$</td><td>Energy loss by valves
$E_{LOSS,VALVE}$</td></tr>
<tr><td colspan="2" rowspan="2">Energy outgoing through water loss
E_{WL}</td></tr>
<tr><td>Input energy by pumps
$E_{IN,PUMP}$</td></tr>
</table>

Figure 2. Energy balance components

Each component for a defined period can be calculated by using the results from the network model, which can be computed as follows:

Input energy to the system by reservoirs, tanks, and junctions

$$E_{IN,TYPE} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{I,TYPE}=1}^{n_{I,TYPE}} Q_{i_{I,T},i_t}(t) * H_{i_{I,T},i_t}(\mathrm{t})\Delta t \tag{5}$$

Input energy to the system by pumps

$$E_{IN,PUMP} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{I,PUMP}=1}^{n_{I,PUMP}} Q_{i_{I,PUMP},i_t}(t) * -\Delta H_{i_{I,PUMP},i_t}(\mathrm{t})\Delta t \tag{6}$$

Energy outgoing through nodes

$$E_{OUT,TYPE} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{O,TYPE}=1}^{n_{O,TYPE}} Q_{i_{O,T},i_t}(t) * H_{i_{O,T},i_t}(\mathrm{t})\Delta t \tag{7}$$

Energy outgoing through water loss

$$E_{WL} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{WL}=1}^{n_{WL}} q_{i_{WL},i_t}(t) * H_{i_{WL},i_t}(\mathrm{t})\Delta t \tag{8}$$

Energy losses in the system by pipe friction and valves

$$E_{LOSS,PIPE} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{L,PIPE}=1}^{n_{L,PIPE}} Q_{i_{L,T},i_t}(t) * \Delta H_{i_{L,T},i_t}(\mathrm{t})\Delta t \tag{9}$$

$$E_{LOSS,VALVE} = \gamma \cdot \sum_{i_t=1}^{n_t} \sum_{i_{L,VALVE}=1}^{n_{L,VALVE}} Q_{i_{L,T},i_t}(t) * \Delta H_{i_{L,T},i_t}(\mathrm{t})\Delta t \tag{10}$$

where H represents the energy head at a node, ΔH denotes head loss, and γ stands for the specific weight of water. The additional subscripts of i and n are L, $PIPE$, $VALVE$, and $PUMP$, denoting loss, pipe, valve, and pump, respectively. In the EPANET model, pumps are categorized as a link type, so pump head is considered as negative head loss.

2.3 Chlorine mass balance calculation

Figure 3 illustrates the components of the chlorine mass balance in WDNs in this study. It provides details about the input, output, loss, and changes sides. On the input side, the system input mass (M_{IN}) represents the total chlorine mass entering a WDN. The output side comprises two components: mass delivered to users (M_{USER}) and outgoing mass through water losses (M_{WL}). On the loss side, the mass losses by reactions (M_{RT}) represent the total chlorine mass loss in a WDN, which can come from pipes ($M_{RT,PIPE}$) and tanks ($M_{RT,TANK}$). On the changes side, the mass changes in networks (ΔM_N) represent the total mass change in a WDN, which can come from pipes ($\Delta M_{N,PIPE}$) and tanks ($\Delta M_{N,TANK}$).

<table>
<tr><td rowspan="6">System input mass
M_{IN}</td><td colspan="2">Mass delivered to users
M_{USER}</td></tr>
<tr><td colspan="2">Outgoing mass through water losses
M_{WL}</td></tr>
<tr><td rowspan="2">Mass losses by reactions
M_{RT}</td><td>Mass losses by reactions in pipes
$M_{RT,PIPE}$</td></tr>
<tr><td>Mass losses by reactions in tanks
$M_{RT,TANK}$</td></tr>
<tr><td rowspan="2">Mass changes in networks
ΔM_N</td><td>Mass changes in pipes
$\Delta M_{N,PIPE}$</td></tr>
<tr><td>Mass changes in tanks
$\Delta M_{N,TANK}$</td></tr>
</table>

Figure 3. Chlorine mass balance components

For the input and output chlorine mass balance components, each component for a defined period can be calculated by the cumulative of the product between the chlorine concentration (C) and the discharge (Q) for a defined period (Δt) as follows:

System input chlorine mass

$$M_{IN} = \sum_{i_t=1}^{n_t} \sum_{i_I=1}^{n_I} C_{i_I,i_t}(t) Q_{i_I,i_t}(t) \Delta t \tag{11}$$

Mass delivered to users

$$M_{USER} = \sum_{i_t=1}^{n_t} \sum_{i_{USER}=1}^{n_{USER}} C_{i_{USER},i_t}(t) Q_{i_{USER},i_t}(t) \Delta t \tag{12}$$

Outgoing mass through water losses

$$M_{WL} = \sum_{i_t=1}^{n_t} \sum_{i_{WL}=1}^{n_{WL}} C_{i_{WL},i_t}(t) Q_{i_{WL},i_t}(t) \Delta t \tag{13}$$

Mass losses by reactions

$$M_{RT} = M_{RT,PIPE} + M_{RT,TANK} \tag{14}$$

$$M_{RT,PIPE} = \sum_{i_t=1}^{n_t} \sum_{i_{PIPE}=1}^{n_{PIPE}} R_{i_{PIPE},i_t}(t) \forall_{i_{PIPE},i_t}(t) \Delta t \tag{15}$$

$$M_{RT,TANK} = \sum_{i_t=1}^{n_t} \sum_{i_{TANK}=1}^{n_{TANK}} R_{i_{TANK},i_t}(t) \forall_{i_{TANK},i_t}(t) \Delta t \tag{16}$$

where R represents the decay rate of chlorine concentration by chemical reactions and $\forall$ means the water volume in each pipe or tank.

Mass changes in networks

$$\Delta M_N = \Delta M_{N,PIPE} + \Delta M_{N,TANK} \tag{17}$$

$$\Delta M_{N,PIPE} = M_{N,PIPE}(t_f) - M_{N,PIPE}(t_o) \tag{18}$$

$$\Delta M_{N,TANK} = M_{N,TANK}(t_f) - M_{N,TANK}(t_o) \quad (19)$$

where t_o and t_f represent the initial and final times, respectively, and the chlorine masses in pipes ($M_{N,PIPE}$) and tanks ($M_{N,TANK}$) are computed as follows:

$$M_{N,PIPE}(t) = \sum_{i_{PIPE}=1}^{n_{PIPE}} C_{i_{PIPE}}(t) \forall_{i_{PIPE}} \quad (20)$$

$$M_{N,TANK}(t) = \sum_{i_{TANK}=1}^{n_{TANK}} C_{i_{TANK}}(t) \forall_{i_{TANK}}(t) \quad (21)$$

3. Software Description

In this section, we describe the software requirements, input and output data, and GUI of KU2EPA-Balances. The package used for performing the hydraulic and water quality simulation in KU2EPA-Balances is the WNTR package in Python. Figure 4 illustrates the flowchart to explain how our software works.

3.1 Software requirements

KU2EPA- Balances requirements include:

- A Python programming environment version 3.7
- WNTR version 0.2.2. installed in Python
- Users should be familiar with EPANET and Python programs.

3.2 Input data

The input data consists of the EPANET-based network model file in INP format, the chosen balance type, the total duration, and the quality time step. The INP file can be generated by exporting from EPANET or manually created in ASCII format identical to EPANET's INP file. The output data comprises hourly and daily balance tables, as well as main and detailed balance component graphs.

3.3 Graphical user interface (GUI)

Figure 5 shows the GUI of KU2EPA- Balances, designed to assist users and divided into seven sections:

- The "INP File" section allows users to import an INP network model file.
- The "Location of Table Results" section allows users to select a folder and name the table result file.
- The "Location of Figure Results" section allows users to select a folder and name the figure result file.
- The "Balance Type" section allows users to select the balance type with three options: Water balance, Energy balance, and Chlorine mass balance.
- The "Total Duration" section allows users to select the model's total duration in hours.
- The "Quality Timestep" section is required when calculating the chlorine mass balance type and allows users to select the water quality simulation timestep in seconds.
- The "Progress" section allows users to start the computation and displays the computation progress in percentages.

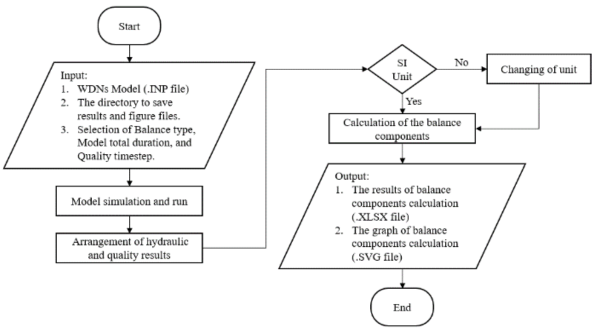


Figure 4. Flowchart of KU2EPA-Balances

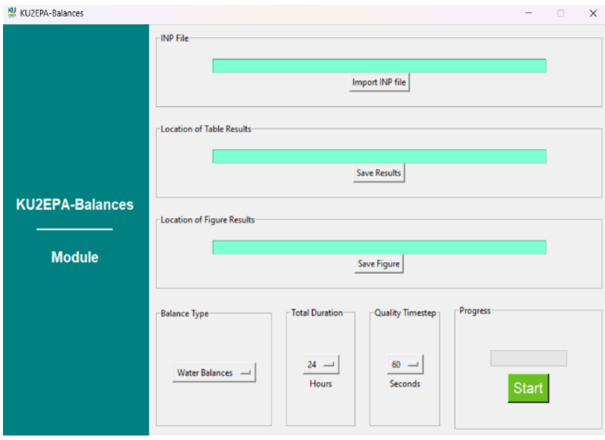


Figure 5. KU2EPA-Balances graphical user interface

4. Water Distribution Network Example

Figure 6 displays a simplified WDN structure consisting of a reservoir, a pump, a tank, junctions, pipes, and a valve. Potable water is pumped from the source (Node 1) to the junction (Node 2). If the energy received from the pump (Link 11) surpasses the energy in the tank (Node 10), the water will flow into the tank through the connected pipe (Link 10). Conversely, if the energy in the tank is higher, the water will flow out of the tank. From the junction, water passes the valve (Link 12) into the service area, consisting of pipes and junctions

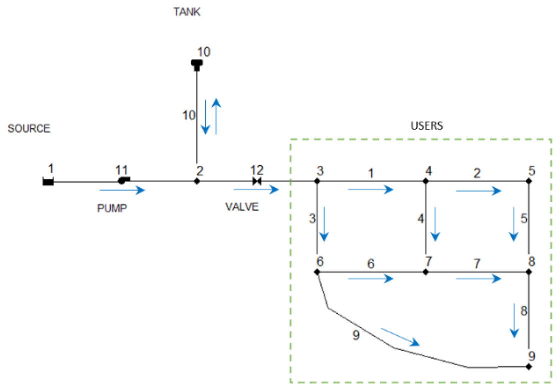


Figure 6. Water distribution network example, where arrows show flow directions, and service area is in dashed rectangle.

where users consume water. This example aims to demonstrate the functionality of KU2EPA-Balances. Table 1 shows the properties of nodes and links. The reservoir (Node 1) is characterized by a total head of -1 m and an initial quality of 1 mg/l. The tank (Node 10)'s attributes include an elevation of 15 m, an initial water level of 5 m, a minimum water level of 0 m, a maximum water level of 10 m, and a diameter of 3 m. The pump (Link 11) has the performance with the designed flow of 70 m^3/hr and the designed head of 30 m. The valve (Link 12) in use is a pressure-reducing valve with a control routine as follows:

- Setting pressure: 20 m at 12:00 AM.
- Valve open: 6:00 AM.
- Setting pressure: 25 m at 12:00 PM.

For leakage, the simulation employs the emitter function in (4) with an emitter coefficient (c) of 0.2 and an emitter exponent (N_1) of 0.5 for all junctions. The initial conditions can impact the results during the early stages of the simulation. Therefore, this network example is simulated for a total duration of 96 hours with a quality timestep of 1 second. The results will be explained in the next section.

Table 1. Nodes and links properties

Node	Base demand (m^3/hr)	Link	Diameter (mm)	Length (m)	Roughness (H-W)
1	*	1	100	200	115
2	0	2	100	200	115
3	10	3	100	200	115
4	10	4	100	200	115
5	10	5	100	200	115
6	10	6	50	200	115
7	10	7	50	200	115
8	10	8	50	200	115
9	5	9	50	500	115
10	*	10	100	200	115
		11	*	*	*
		12	100	*	*

* Node 1 is a reservoir, Node 10 is a tank, Link 11 is a pump and Link 12 is a valve. The properties of these nodes and links are described in the context.

5. Results and Discussion

5.1 Water balance results

Figure 7 shows the simulation's water balance results. The daily water balance for Day 1, shown in Figure 7a, is indicated by two pie charts, inflow and outflow. From the inflow chart, the majority of the system input volume (W_{IN}) is sourced from the resource ($W_{IN,RES}$). From the outflow chart, most of the water exiting the system (W_{OUT}) is delivered to users as $W_{OUT,USER}$. The water loss is 162.02 m3/day, accounting for 9.31% of W_{IN}. Additionally, the difference between $W_{IN,TANK}$ and $W_{OUT,TANK}$ reveals that a portion of W_{IN} (48.96 m3/day, calculated as 96.55 – 47.59) is used to fill the tank.

Figure 7b illustrates the hourly time series of water balance components ($W_{IN,RES}$, $W_{IN,TANK}$, $W_{OUT,TANK}$, $W_{OUT,USER}$ and W_{WL}) over 96 hours. Notably, the patterns of $W_{IN,RES}$ and $W_{OUT,USER}$ exhibit similarities. During the morning peak of water use, the system is partially supplied by the tank, leading to a sudden spike in $W_{IN,TANK}$. Subsequently, the tank is refilled, as indicated by a spike in $W_{OUT,TANK}$ immediately after the morning peak. The consistent value of W_{WL} over time indicates a constant rate of water loss due to the stable system pressure under the valve control.

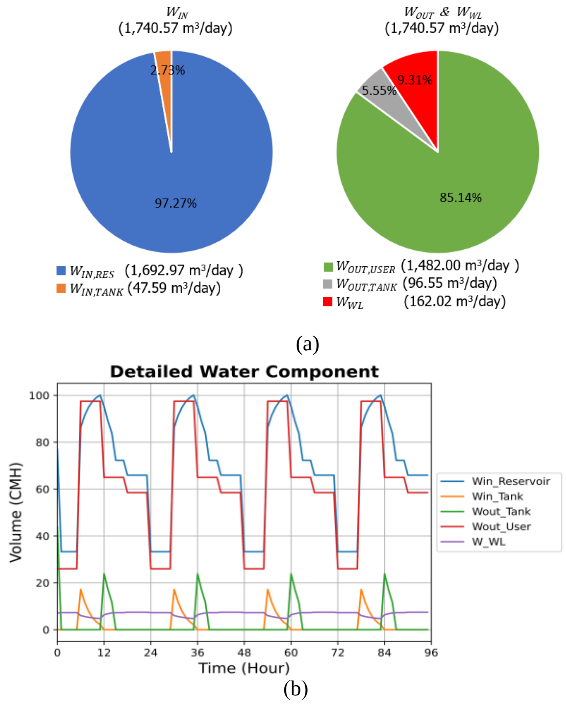
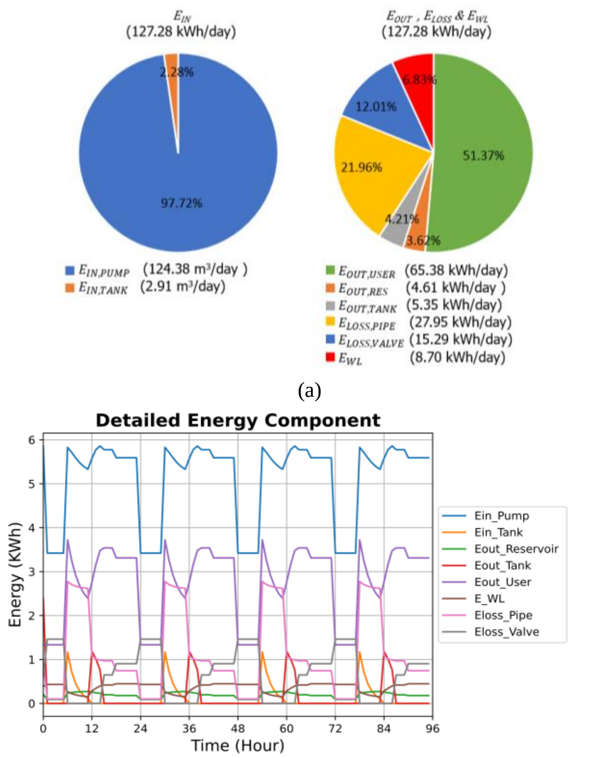


Figure 7. Water balance results with (a) daily balance for Day 1, and (b) hourly balance over 96 hours

5.2 Energy balance results

Figure 8 presents the simulation's energy balance results. The daily energy balance for Day 1 is illustrated into two pie charts as input and output energies in Figure 8a. The input energy chart reveals that the primary source of system input energy (E_{IN}) is the pump ($E_{IN,PUMP}$). While the water balance indicates that W_{OUT} is 90.69% of W_{IN} in Figure 7a, the energy outgoing through nodes (E_{OUT}) is only 59.20% of E_{IN} in the output energy chart. The discrepancy is attributed to the energy dissipated (E_{LOSS}), which accounts for 33.97% of E_{IN}. The difference between $E_{IN,TANK}$ and $E_{OUT,TANK}$ indicates that a portion of E_{IN} (2.44 kWh/day, calculated as 5.35 – 2.91) is stored in the tank, consistent with the tank's results in the water balance. In this particular example, $E_{IN,RES}$ is zero, while $E_{OUT,RES}$ is 4.61 kWh/day due to the negative total energy head of the reservoir.

Figure 8b illustrates the hourly time series of water balance components ($E_{IN,PUMP}$, $E_{IN,TANK}$, $E_{OUT,RES}$, $E_{OUT,TANK}$, $E_{OUT,USER}$, E_{WL}, $E_{LOSS,PIPE}$, and $E_{LOSS,VALVE}$ over 96 hours. Notably, the patterns of $E_{IN,PUMP}$ and $E_{OUT,USER}$ exhibit similarities with a larger gap compared to the patterns of $W_{IN,RES}$ and $W_{OUT,USER}$ in the water balance due to energy dissipation. The pattern of E_{WL} over time is similar to W_{WL}, as both are influenced by system pressure. The morning peak of water use at 6:00 AM leads to a sudden increase in $E_{LOSS,PIPE}$, which gradually decreases until the next morning. $E_{LOSS,VALVE}$ is observed to depend on the valve control settings.



(a)

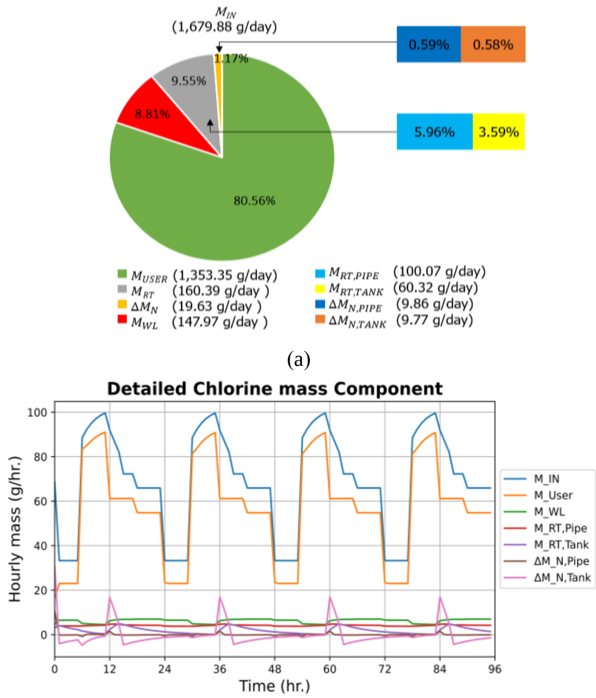
(b)

Figure 8. Energy balance results with (a) daily balance for Day 1, and (b) hourly balance over 96 hours

5.3 Chlorine mass balance results

Figure 9 shows the simulation's chlorine mass balance results. The daily chlorine mass balance for Day 1, as presented in Figure 9a, reveals that the system input mass (M_{IN}) is 1,679.88 g/day. Of this, a substantial portion, amounting to 1,353.35 g/day, is delivered to users (M_{USER}), accounting for 80.56% of M_{IN}, while the outgoing mass through water losses (M_{WL}) is 147.97 g/day, accounting for 8.81% of M_{IN}. Additionally, the mass losses by reactions (M_{RT}) are 160.39 g/day, accounting for 9.55% of M_{IN}. The chlorine mass changes (ΔM_N) amount to 19.63 g/day, which indicates the network requires an additional mass input to achieve balance. This required mass is a result of the initial conditions in this example, where there is no initial chlorine within the tank and pipes. When the network continuously operates over a prolonged period with numerous cycles of periodic patterns, ΔM_N will gradually approach zero.

Figure 9b illustrates the hourly time series of chlorine mass balance components (M_{IN}, M_{USER}, M_{WL}, $M_{RT,PIPE}$, $M_{RT,TANK}$, $\Delta M_{N,PIPE}$, and $\Delta M_{N,TANK}$, over 96 hours. Notably, the patterns of M_{IN} and M_{USER} exhibit similarities. During refilling of the tank, chlorine is restored in the tank, leading to a sudden spike in $\Delta M_{N,TANK}$. Subsequently, $M_{RT,TANK}$ is increasing because of the decomposition of chlorine occurring inside the tank.



(a)

(b)

Figure 9. Chlorine mass balance results with (a) daily balance for Day 1, and (b) hourly balance over 96 hours

5.4 Relationship between water losses, energy losses and chlorine losses

Mamade *et al.* (2018) first explored the relationship between water losses and energy losses. Analyzing simulation results from 20 real networks in Portuguese water distribution systems, they observed that the percentage of energy outgoing through water loss (E_{WL}) approximately equals the percentage of water losses (W_{WL}). Later, Lipiwattanakarn *et al.* (2021a) conducted a theoretical energy balance analysis on simplified pipe networks and proposed a method indicating that the percentage of E_{WL} is actually smaller than the percentage of W_{WL} due to energy head loss. Our 1-day results show that the percentage of E_{WL} is 6.83% smaller than the W_{WL} percentage of 9.31%, agreeing with Lipiwattanakarn *et al.* (2021a)'s theory.

Recently, Wongpeerak *et al.* (2023) investigated the relationship between water losses and chlorine losses using a theoretical analysis similar to Lipiwattanakarn *et al.* (2021a). Their findings indicate that the percentage of outgoing mass through water losses (M_{WL}) is also smaller than the percentage of W_{WL}. Our results confirm this theory, with the percentage of M_{WL} at 8.81% being smaller than the W_{WL} percentage of 9.31%.

5.5 Benefits of water, energy and chlorine mass balances

Using water balance and energy balance analyses, Lipiwattanakarn *et al.* (2019) assessed the benefit of leak surveys and repairs of a water distribution network in the service area of Metropolitan Waterworks Authority (MWA) in Bangkok, Thailand. By comparing water and energy balances before and after the repairs, they observed a 9% reduction of inflow volume to the network. Additionally, the input energy decreased by 8%, while the pressure and energy delivered to customers increased by 8%. To determine the monetary benefit, they compared the cost of leak surveys and repairs with the benefits gained from reduced water production and energy consumption. The study recommended that MWA undertake more aggressive leak surveys and repairs based on these positive outcomes. This example demonstrates the effectiveness of water, energy, and chlorine mass balances in evaluating the benefits and losses of various activities or events. By comparing the changes in each component of water, energy, and chlorine mass balances, the benefits and losses can be assessed in terms of monetary value or service level. Our KU2EPA-Balances software provides a convenient tool for researchers and practitioners to analyze these balances effortlessly.

6. Conclusions

All potable water systems are dealing with water losses, energy losses and water quality deterioration. These losses not only result in the wastage of water resources, electrical energy, and chlorine but can also lead to the worsening or even disruption of service to users. The balance concept is widely recognized and adopted to audit and control these losses. Water distribution networks (WDNs) are typically the largest components of potable water systems in terms of size and pipe length, making them the most complex system to manage in terms of these losses.

However, there is currently no prior modelling tool available that can comprehensively analyze and provide insights into these three critical aspects together. This paper introduces KU2EPA-Balances, a new Python-based software designed to assist water utilities in the calculations of water, energy, and chlorine mass balances and losses in WDNs. KU2EPA-Balances utilizes WNTR, a Python package that integrates hydraulic and water quality simulations. WNTR is built on the foundation of EPANET, the most renowned software for simulating the movement and fate of potable water constituents in pressurized distribution systems. The KU2EPA-Balances software has been applied to 20 real water distribution networks in the service area of Metropolitan Waterworks Authority, Thailand (Lipiwattanakarn *et al.*, 2021a; Wongpeerak *et al.*, 2023) and verified through manual calculations.

KU2EPA-Balances requires the EPANET input file, consisting of the pipe network structure and properties such as pipes, pumps, tanks, reservoir, valves, operational conditions, etc. The software has demonstrated capacity to accurately compute water, energy, and chlorine mass balances even on short hourly timescales. In terms of water balance, the software provides information on the volume of water loss corresponding to system pressure. Regarding energy balance, it offers insights into energy losses, including energies dissipated by pipes and valves, as well as energy leaving the system through leakage. In the context of chlorine mass balance, the software evaluates chlorine mass losses due to the chemical reactions in pipes and tanks, as well as outgoing chlorine mass through leakage. The information provided by KU2EPA-Balances can help water utilities to plan suitable system operations, maintenance, and improvements to achieve benefits in terms of water, energy and water quality in water distribution systems.

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