Water Consumption Studies of Domestic Housing in Hong Kong – A Pilot Study using Smart Water Auditing Technology

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Abstract:
For the purpose of water conservation in Hong Kong, a more comprehensive and precise water consumption profile of domestic housing should be extracted. Smart Water Auditing system, proposed by the HKU Centre for Water Technology and Policy (Water Centre), is an innovative technology integrated with the use of smart water meters and Internet of Things (IoT) data transmission technology to achieve the goal. Our project is the pilot study phase of an interdisciplinary project aiming to help develop this initiated technology by evaluating the performance of the smart water meters and flow sensors through laboratory tests and collecting household water use data for consumption pattern analysis through carrying out field tests. A laboratory test rig was created for conducting laboratory tests on the water meters to verify their performance at different physical conditions. The volume of water recorded by the water meters was compared with the actual volume obtained by gravimetric method. Until now, the laboratory test results show that the percentage errors of the 3 flow sensors (SIKA VTY 10 brass, SIKA VTY 20 brass and SIKA VTY 10 plastic) are able to maintain within acceptable limits of 5%. For the field tests, the results illustrated that different households had their own water consumption patterns which give an insight of the normal water consumption patterns of the occupants.

Keywords:
Smart Water Auditing, smart water meter, Internet of Things, domestic household, water consumption studies

1. Introduction

1.1. Background

Smart Water Auditing system is an innovative method to obtain a more comprehensive water consumption profile of domestic households. It aims to achieve the goal of water conservation. Household members can improve their water usage by understanding their water consumption profile in mobile devices through the Smart Water Auditing system to achieve the goal.

1.2. Conceptual Framework of Smart Water Auditing System

Smart Water Auditing system applies the concept of IoT to generate detailed policy-relevant domestic water use data by making use of a combination of IoT tools including smart water meters, wireless communication technologies and machine learning algorithms. The research findings of this large-scale project can ultimately help fill a major gap in our knowledge on the composition of end uses of water by type of use in the domestic sector in Hong Kong.

Figure 1 shows the schematic grid of the Smart Water Auditing system and its process, starting from the water usage points to the mobile devices where data is received via the cloud system as a medium for transmission of the data. First, smart water meters installed near the government billing meter, together with water flow sensors installed into the water usage points such as kitchen taps and shower heads will collect water flow data of the household. Second, the data will be transmitted via Wi-FI and internet and stored in the cloud database, which will then be sent to a data cluster for machine learning. The machine learning algorithms will then start analyzing and obtaining water usage disaggregation, with specific types of end uses such as flushing, dishwashing and showering being clearly displayed. Lastly, users can read their water usage minutely and remotely through internet browser and more importantly to reflect their water consumption profile and hence allowing them to change their behavior.

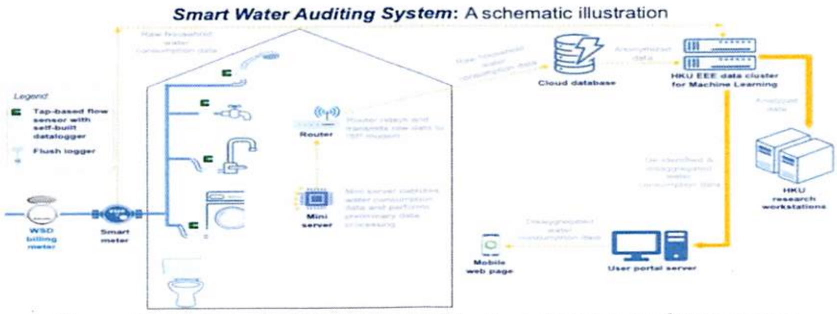


Figure 1. A schematic illustration of the Smart Water Auditing system
Source: Adapted from [1]

1.3. Objectives

The project involves collaboration of the HKU Water Centre, the Department of Mechanical Engineering and the Department of Electrical & Electronic Engineering. We participated this interdisciplinary project as a team to work on the mechanical parts and further studied the Smart Water Auditing technology. This project has a few phases, the pilot phase being the evaluation of the performance of devices in the Smart Water Auditing system, such as flow sensors and water meters and the collection of the water use data in households to analyse their water consumption patterns. These goals can be achieved by conducting a series of laboratory tests and field tests on both the software and hardware devices of the Smart Water Auditing system. Tests on accuracy, reliability and accessibility of the Smart Water Auditing system need to be done before this technology is introduced to the next phase when hundreds of households will be studied.

2. Laboratory Test

2.1. Introduction

In the beginning of the Smart Water Auditing project, several potential water meters and tap-based flow sensors were considered to be installed in households for collecting water use data. In order to choose the most appropriate measuring devices for collecting the data, a series of laboratory tests were conducted to evaluate the performance of tap-based flow sensors and water meters. Also, the test aimed at verifying the characteristic curves of the flow sensors so as to improve the accuracy of the measured results.

2.2. Objectives

The objectives of the laboratory test are:

1. To verify the characteristic curves of flow sensors (SIKA VTY10 brass, SIKA VTY10 plastic and SIKA VTY20 brass).
2. To evaluate the performance of flow sensors and water meters (Elster V200, Sensus iPERL and Huizhong SCL-61H) under different operation conditions.

2.3. Devices to be Tested

	Sensus iPERL	Elster V200	Huizhong SCL-61H
Meter types	Electromagnetic	Volumetric mechanical meter	Ultrasonic
Reading Resolution	3 decimal places (1 L)	4 decimal places (0.1 L)	5 decimal places (0.01 L)
Data transmission method	RF radio (drive by)	3G (SMS)	NB-IoT
Minimum data logging method	≤ 1 minute	1 second	10 seconds
Maximum water pressure (bar)	16	16	16
Maximum water temperature (°C)	70	30	70

Table 1. Specifications of water meters
Source: Adapted from [2], [3], [4]

	SIKA VTY10 brass	SIKA VTY10 plastic	SIKA VTY20 brass
Process connection	G1/2 male thread	G3/4 male thread	G1/ male thread
Output signal	Square wave	Square wave	Square wave
Pulse rate (no. of pulses/L)	495	520	119
Medium temperature (°C)	0-90	0-85	0-90
Flow range (L/min)	1-30	1-30	1-60

Table 2. Specifications of flow sensors
Source: Adapted from [5], [6]

2.4. Methodology

2.4.1. Laboratory Test Setup

As for the main water supply pipe, a S-shape pipework was adopted to allow the water flowing through all flow sensors and water meters at the same time in every testing (see Figure 2). Readings of the water meters could be recorded manually and the flow sensors were connected to self-built data loggers to send out readings to an online dashboard. In order to simulate different operation conditions, a water heater was installed to alter the water temperature and a pneumatic pump was installed to adjust the pressure. In the setup, different kinds of water taps were installed, such as basin, kitchen sink and shower heads.

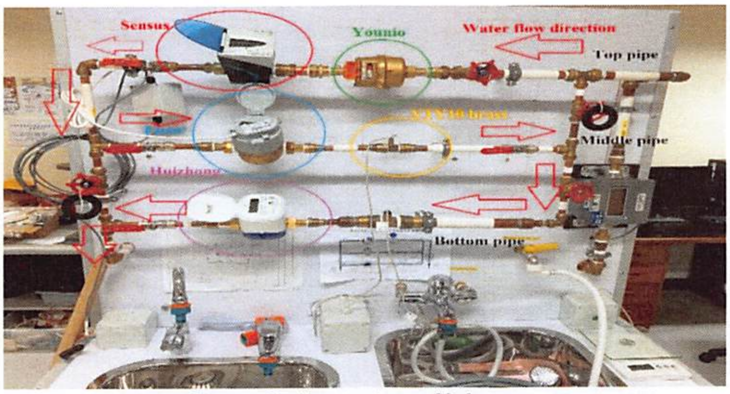


Figure 2. Front view of laboratory test setup

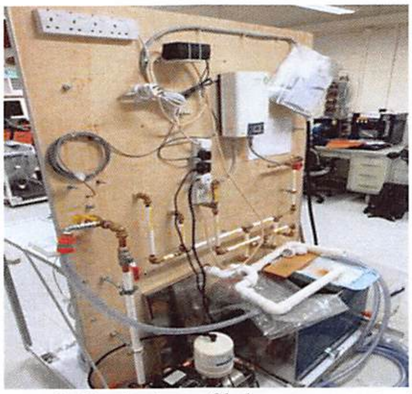


Figure 3. Back view of laboratory test setup

2.4.2. Assessment Criteria

Gravimetric method is used to evaluate the accuracy of tap-based flow sensors and water meters. As for procedures of the gravimetric method, weight of water will be measured using an electronic balance and this result is compared with the readings of water meters and flow sensors to see whether the percentage errors of flow sensors and water meters are within an acceptable range of ± 5%. The percentage error is calculated as follows:

Percentage error of water meter:

$$\frac{V_{meter} - \frac{m_{water}}{\rho_{water}}}{\frac{m_{water}}{\rho_{water}}} * 100\% .. (1)$$

Percentage error of flow sensor:

$$\frac{V_{flow\ sensor} - \frac{m_{water}}{\rho_{water}}}{\frac{m_{water}}{\rho_{water}}} * 100\% .. (2)$$

Where V_{meter} = volume of water measured by water meter, $V_{flow\ sensor}$ = volume of water measured by flow sensor, m_{water} = mass of water measured by gravimetric method, ρ_{water} = density of water.

2.5. Results of Laboratory Test

A series of laboratory tests had been successfully conducted to evaluate the performance of tap-based flow sensors and water meters in the Smart Water Auditing system under different operation conditions. The results are as follows:

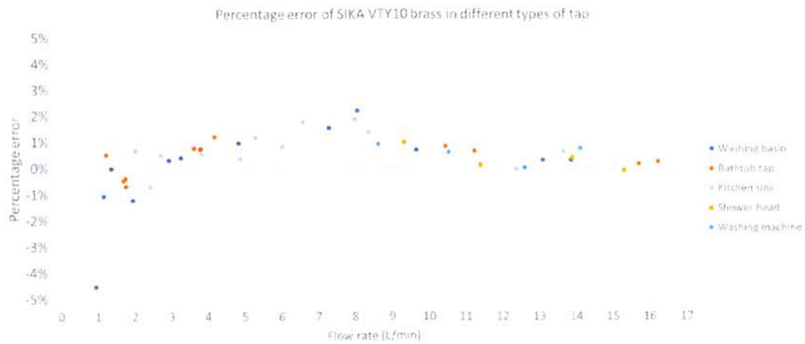


Figure 4. Percentage error of SIKA VTY10 brass in different types of tap under different flow rates

Figure 4 shows the percentage errors when SIKA VTY10 brass was tested in various types of tap. Most of the percentage errors range from + 2% to – 1%.

Figure 5. Percentage error of SIKA VTY10 brass in 40°C and 60°C

Figure 6. Overall Performance of SIKA VTY10 brass, VTY10 plastic and VTY20 brass

Figure 5 shows the percentage errors do not exceed ± 5% at various flow rates at 40°C and 60°C. Figure 6 shows the percentage errors of SIKA VTY10 brass, VTY10 plastic and VTY20 brass are able to stay within ± 5% mostly.

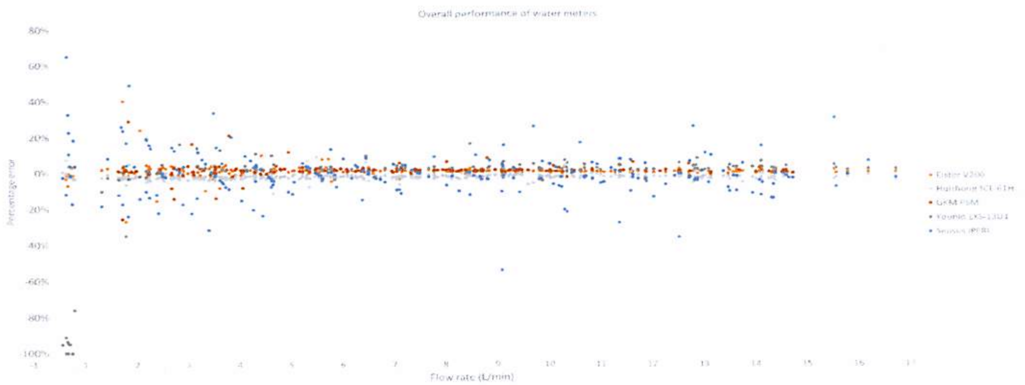


Figure 7. Overall performance of water meters

In Figure 7, it is observed that the percentage errors of Sensus iPERL disperse significant under low flow conditions. Most of the percentage errors of Elster V200 lie within ± 5% at different flow rate. However, there are some percentage errors exceeding 5% and reaching over 20% between 1 L/min and 6 L/min. As for Huizhong SCL-61H, the percentage errors generally stay within ± 5%.

2.6. Discussion of Laboratory Test

2.6.1. Influence of Water Temperature on Performance of SIKA VTY10 brass

It is observed that when SIKA VTY10 brass operates at 40 °C or 60 °C, the percentage errors still lie within ± 5%. This result is expectable because according to Table 2, SIKA VTY10 brass is able to operate at a medium temperature from 0 °C to 90 °C. Since the maximum water temperature in households is usually 60 °C for water heater, there is no doubt that the flow sensors could provide accurate readings within this range of water temperature.

2.6.2. Influence of Type of Tap on Performance of SIKA VTY10 Brass

According to Figure 4, it is observed that when SIKA VTY10 brass operates in different types of tap, such as washing basin and kitchen sink, the percentage errors lie within ± 5%. Therefore, the type of tap does not affect the performance and accuracy of SIKA VTY10 brass.

2.6.3. Limitations of Flow Sensors

Although the flow sensors are able to measure volume of water accurately under different operation conditions (water temperature, type of tap), the flow sensors are not capable of measuring water flow under ultra-low flow conditions ($Q < 1$ L/min). According to the specifications (see Table 2), the minimum detectable flow rate for SIKA VTY10 brass, VTY10 plastic and VTY20 brass is 1 L/min. It implies that they cannot give out readings under 1 L/min and thus in Figure 6, there is no percentage error of flow sensors under 1 L/min. If there is a water use event with a flow rate smaller than 1 L/min, the flow sensors are not able to detect the water flow fundamentally.

2.6.4. Overall Performance of Water Meters

The performance of water meters from the best to the poorest can be ranked as follows:
Huizhong SCL-61H = Elster V200 > Sensus iPERL

As for Elster V200 and Huizhong SCL-61H, their performance is the most satisfactory and comprehensive because the percentage errors of them at different flow rates stay within ± 5% generally (see Figure 7). Also, the volume of water measured has a minimal impact on their performance because the resolution levels of Elster V200 and Huizhong SCL-61H are 4 and 5 decimal places respectively. Therefore, the volume of water is low, the performance will not be influenced significantly.

Sensus iPERL is the least accurate meter among all because the performance is mainly subjected to the volume of water measured because the resolution level is only 3 decimal places when comparing with the resolution level of other water meters.

To conclude, it is preferable to install Elster V200 or Huizhong SCL-61H in household fields to collect real water use data due to their stable performance at different flow rates.

3. Field Test

3.1. Objectives

The objectives of the field tests are:

1. To verify that the equipment tested in the laboratory is intact for actual field tests to be carried out afterwards.
2. To test the performance of the smart metering system in the field.
3. To collect preliminary water usage data including consumption pattern from the households.

3.2. Methodology

At each household, one water meter was installed by a licensed plumber at an effective distance from the existing government water meter to minimize the interference with the meter. SIKA flow sensors on each tap and a toilet float switch were also installed. The mini server of the household could capture the water consumption data transmitted by each device through Wi-Fi and perform preliminary data processing.

There were some points we need to pay attention to. First, we had to keep draining the water in the shower tube after turning off the tap. Also, all of the water from the bucket and electronic balance surfaces had to be removed each time before testing in order to minimize the measurement errors. Last, we had to dry the wires with a towel before testing and connect the wiring before switching on the power to prevent electric shock.

3.3. Preliminary Results and Analysis

The water metering devices had been successfully installed in three households. The first set of data (18/3-12/4) generated by the SIKA flow sensors was collected and analysed in 24-hour format. Each household was given an ID and the data we collected were from household ID 3, 7 and 9. Household ID 3 and 9 had the household size of 1 member, while household ID 7 had the household size of 2 members. Household ID 3 and 7 had bathrooms in both master room and guest room, while household ID 9 had only one bathroom with no bathtub.

3.3.1. Overall Fresh Water Consumption Composition

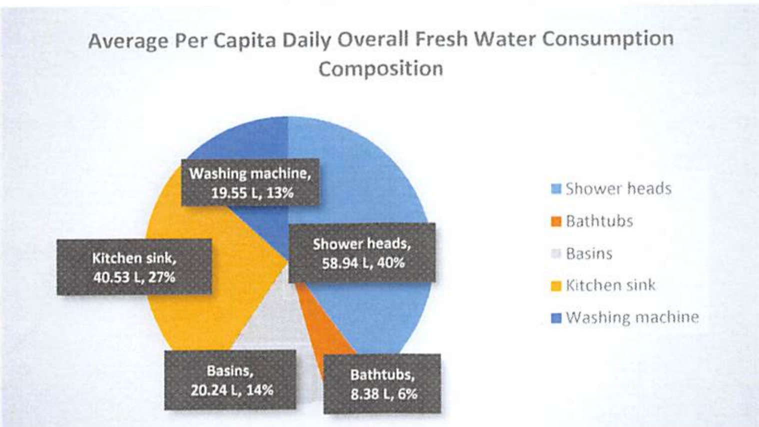


Figure 8. Average per capita daily overall fresh water consumption composition

From the data generated by the SIKA flow sensors, it is observed that domestic fresh water was mainly consumed through shower heads (58.94 L, 40%) and kitchen sink (40.53 L, 27%), followed by basins (20.24 L, 14%) and washing machines (19.55 L, 13%) as shown in Figure 8. Bathtubs (8.38 L, 6%) accounted for the least proportion of the overall composition.

3.3.2. Average Daily Fresh Water Consumption Per Capita

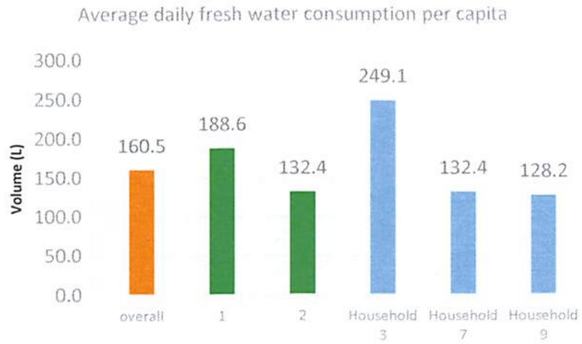


Figure 9. Average daily fresh water consumption per capita of the three households

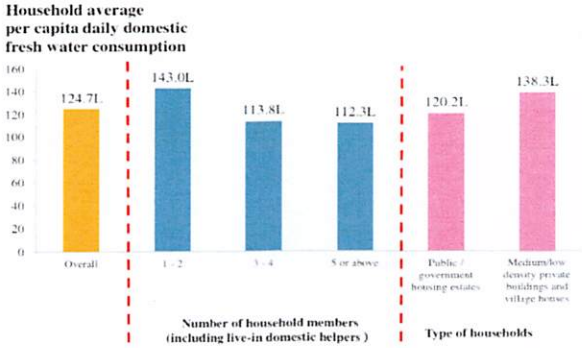


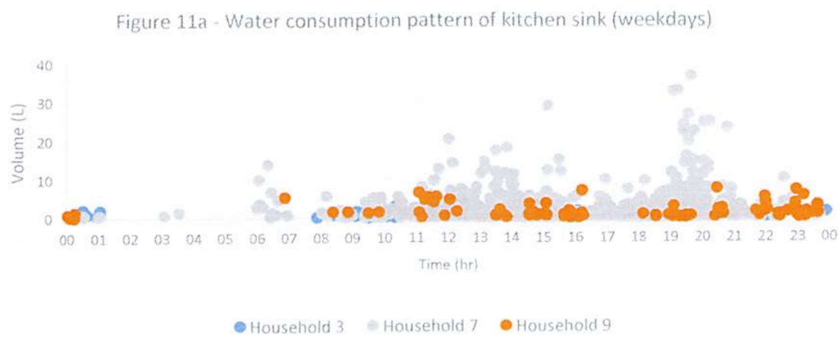
Figure 10. Average daily fresh water consumption per capita in HK in 2011 by WSD [7]

As shown in Figure 9, the field tests show that household ID 3, 7 and 9 had the average daily fresh water consumption per capita of 249.1 L, 132.4 L and 128.2 L respectively, while the overall average daily fresh water consumption per capita of the three households was 160.5 L. Figure 10 shows that the average daily fresh water consumption per capita with household size 1-2 in Hong Kong in 2011 was 143.0 L. It is observed that the WSD underestimated the daily water consumption of people in Hong Kong by 11%. This result suggests that the WSD's methodology of collecting the water consumption data by asking the households to maintain a self-reported logbook to record their water usage details, was inaccurate.

3.3.3. Water Consumption Pattern

Different water consumption patterns can be observed in three different households. It is due to the diverse water consumption activities and habits of different people. Here are some of the examples of their water consumption patterns.

3.3.3.1. Kitchen Sink



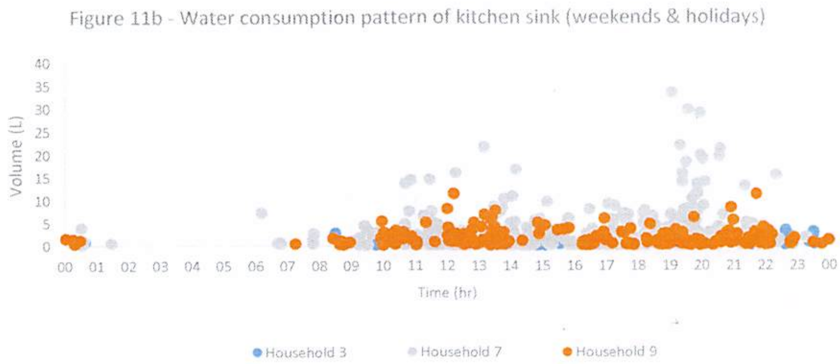
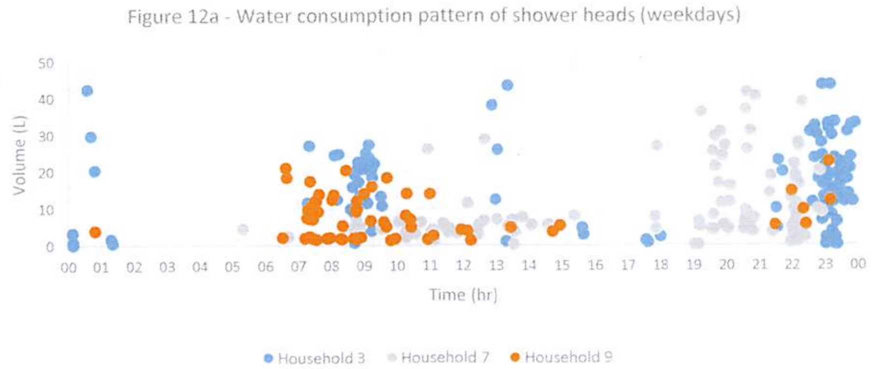


Figure 11. Water consumption pattern of kitchen sink - (a) during weekdays, (b) during weekends & holidays

As shown in Figures 11a & 11b, household ID 7 was more active in using the kitchen sink than other households. It is suggested that household ID 7 involved in cooking activities more frequently than household ID 3 and 9. It is also observed that Household ID 9 used the kitchen sink more during weekends and holidays. In general, all household members often used the kitchen sinks from 11:00-15:00 and 18:00-22:00 as those periods were lunchtime and dinnertime.

3.3.3.2. Shower Heads



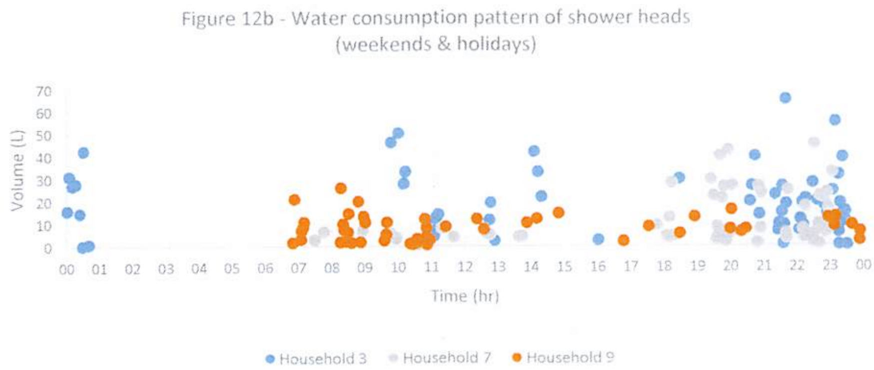


Figure 12. Water consumption pattern of shower heads - (a) during weekdays, (b) during weekends & holidays

We can observe from Figures 12a & 12b that both household ID 7 and 9 had constant water consumption pattern of shower heads during weekdays and weekends. Household ID 7 had more active uses of the shower head at night (18:00-23:00), while household ID 9 had more active uses of the shower head in the morning (07:00-10:00). For household ID 3, there were two time periods during weekdays that the household member was active in using the shower head, which were 07:00-09:00 and 21:00-01:00. However, during weekends, there was zero record of the household member using the shower head from

07:00-09:00. It is suggested that the different active using time of the shower heads were the showering time of the different households.

3.3.4. Flow Rate

By comparing the flow rates of each type of taps, we can find out which household's tap is more water-saving. Besides, we can learn about the water use habits for each household in terms of water flow rate. Here is one of the examples. 1 L/min line is drawn to indicate the noises.

3.3.4.1. Shower Heads

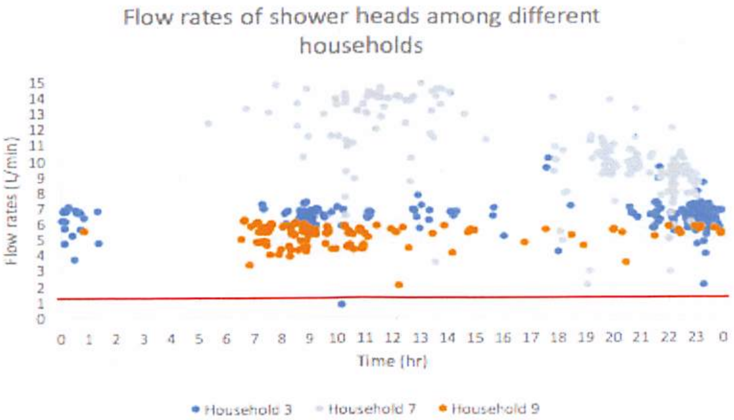


Figure 13. Flow rates of shower heads among different households

From Figure 13, it is observed that the shower heads used in household ID 9 was the most water-saving among the three households while shower heads used in household ID 7 was the less water-saving. For the showering habits, households with one member (household ID 3 and 9) were quite similar. They had a narrow range of flow rates. For household ID 3, around 80% of the number of uses were in the range of 6-8 L/min. For household ID 9, around 90% of the number of uses were in the range of 4-6 L/min. However, households with two members (household ID 7) used water for shower in a wider range of flow rates. Besides, the flow rate patterns divided into two sections. In daytimes (around 07:00-14:00), household members used water at higher flow rates (usually around 11-14 L/min). At night (around 19:00-23:00), they used water at lower flow rates but in a wider range (usually around 6-12 L/min). The diversity of the result of household ID 7 maybe due to the different shower habits from two different household members.

3.3.5. Flush Water

For water used on flushing in WCs, the overall and individual households' average daily number of flush and volume used for flushing per capita were calculated based on the flush data recorded. The result table is shown below.

	Average	Household ID 3	Household ID 7	Household ID 9
Size of cistern (L) (approximate)	N/A	7.5	10	7.5
Number of flush	7.8	8.9	8.1	6.0
Volume used (L)	69.8	66.1	84.3	44.4

Table 3. Average daily number of flush and volume used for flushing per capita

In general, one person had around 8 flushing times in a day while daily volume used was about 70 L.

3.3.6. Water Supply Pipe Sizing in Hong Kong

For plumbing design in Hong Kong, we follow the Plumbing Engineering Services Design Guide in UK [8]. Loading unit is used for water supply pipe sizing determination. The value of loading unit is directly proportional to the design flow rate and use duration for each sanitary fitment. It also depends on the frequency of use and the type of building. A larger pipe size is used for a larger simultaneous water demand (sum up of loading units).

In this project, we discovered that there are large differences between the design guide and the actual data we recorded from the three households. Therefore, a table is constructed to show the variations.

Type of appliance	Design guide		Measured data	
	Flow rate (L/s)	Demand (s)	Average flow rate (L/s)	Average duration (s)
Basin, 15mm sep. taps (bathroom basin)	0.15	33	0.06	19
Sink, 15mm sep./mix tap (kitchen sink)	0.2	60	0.07	26
Bath, 15mm sep./mix tap (bathtub)	0.3	266	0.14	126
Shower, 15mm head (shower head)	0.08	300	0.12	107
Clothes washing m/c, dom. (washing machine)	0.2	25	0.10	10
WC suite, 5 litre cistern (water closet, WC)	0.1	60	7.5 L cistern	
			0.19	39
			10 L cistern	
			0.24	43

Table 4. Comparison between design guide [8] and measured data

In Table 4, it shows that there are large differences on flow rate and duration between the design guide and the measured data. In most of the situations, the measured average flow rate and the average duration used for each type of the sanitary fitments are much smaller than the design guide that we follow in Hong Kong, except for the flow rates of shower head and WC. Besides, the actual capacities of WC are varied and normally larger than the design guide that we follow. Because of the above reasons, we believe that the pipe sizing for fresh water supply is over-estimated while the pipe sizing for flush water supply is under-estimated in Hong Kong. In order to develop a design guide that suit the situation in Hong Kong to give a better estimation in pipe sizing, more research should be done and more water consumption data should be collected.

4. Conclusion

In conclusion, the pilot study has been completed and the goals were achieved. In this project, the performance of water meters and SIKA flow sensors was evaluated through a series of laboratory tests and field tests. For the laboratory tests, the problem of characteristics curve of SIKA flow sensors leading to inaccuracy of the water volume measured under low flow rate has been identified and fixed through laboratory test. It is also found that the Huizhong and Elster water meters were better options among those water meters we have tested in the laboratory tests in terms of the accuracy. Sensus iPERL water meter was the most inaccurate among all the water meters tested. Nonetheless, due to the limitations of water meters in actual scenario, the idea of replacing the water meter with a SIKA flow sensor to record the overall water usage in a household was proposed. For the field tests, water consumption data of three households were collected and analysed and different water consumption patterns can be observed, suggesting the diverse water consumption habits of different households. In the future, more field tests will be conducted in 500 households for collecting more data and pattern analysis.

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