Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.889609

54 (2015) 1401–1409
April

Field application of waterworks automated meter reading systems and analysis of household water consumption

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Received 22 November 2013; Accepted 25 January 2014

ABSTRACT

After the construction of waterworks automated meter reading (AMR) systems with a 15-mm diameter smart water meter developed in this study, both the feasibility of field application of waterworks AMR and the patterns of household water consumption were evaluated. Average reception rate was 94.1% due to the communication blackout, and one-to-one communication with RF UHF and Internet (i.e. TCP/IP) was found to be more stable in AMR systems than multiple-to-one communication with RF UHF, DCU, and Wibro. Household water consumption clearly showed seasonal periodicity due to weather factors. Based on the analysis of liters per capita day (LPCD) for 80 households, the LPCD values were found to decrease gradually as the number of residents increased due to the saving effects through common consumption (i.e. washing, cooking, cleaning, irrigation, etc.). Relative to LPCD values of 100 control households without AMR systems, the LPCD values of 80 pilot households with AMR systems were reduced by 5.3%. Consequently, the deployment of developed waterworks AMR systems integrating smart water metering and end-use water consumptions should be encouraged to conserve both water and energy for smarter cities.

Keywords: Automated meter reading (AMR); Communication; Household water consumption; Liters per capita day (LPCD); Smart water meter

1. Introduction

Recently, “Smart Water Grids” have been proposed as the promising concept of water resource management to overcome the limits of the existing water management systems with better measurement, communications, analysis, and control [1–11]. Smart Water Grids are defined as intelligent water management systems that efficiently supply, distribute, and manage various water resources (e.g. river water, rainfall, groundwater, waste-water, seawater, etc.) to solve the water scarcity by using advanced information communication technology (ICT) [1–11].

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Presented at the 6th International Conference on the “Challenges in Environmental Science and Engineering” (CESE-2013), 29 October–2 November 2013, Daegu, Korea

In general, Smart Water Grids are composed of two main technologies: (1) water management technology to collect various water resources in water platforms and to physically control supply, distribution, and management; and (2) integrated information technology based on ICT to support real-time control of supply, distribution, and management for various water resources [1–11]. For example, Smart Water Grids that have been applied in USA include these technologies: (1) advanced metering infrastructure (AMI), (2) optimization of water–energy nexus, (3) sensor networks for managing quantity and quality of water resources, (4) efficient integrated management systems, and (5) various forms of convergence technologies such as management of water resources based on cloud computing [2,5,8,9].

Among major technologies in Smart Water Grids, AMI can be defined to include: (1) various smart meters and associated peripherals to measure, transmit, and analyze data on the consumption of water and the status of the meters; (2) software, communication methods, and integrated management systems [12–20]. The AMI is generally divided into automated meter reading (AMR), automated meter management, and smart metering [20].

Since waterworks AMR can collect water consumption and additional data (e.g. continuous flow, reverse flow, tamper alert information, etc.) and transmit those data on a daily or more frequent basis, it has the capabilities: (1) to resolve complexity in meter reading due to continuous increase of consumers; (2) to prevent meter reading errors and to ensure information tasks of both water consumption and bills; (3) to save water by detecting the leakage through real-time analysis of water consumption [12–20]. As several local governments in Republic of Korea started adopting waterworks AMR systems after 2002, many smart water meters have been developed and improved [21,22]. However, types and communication methods of smart water meters are not yet standardized, and no direct investigation has previously been performed to collect real-time information on water consumption, to analyze the pattern of household water consumption, and to evaluate the water savings by adopting waterworks AMR systems.

Therefore, in this study, a 15 mm-diameter smart water meter was developed and installed in 80 households out of 320 households in the apartment complex located in B-gu, Incheon City. Then, both real-time information on water consumption and patterns of household water consumption through waterworks AMR systems were analyzed. As mentioned above, the main objectives of this study are: (1) to evaluate the field performance and applicability of waterworks AMR systems in certain apartment complex of Republic of Korea, (2) to analyze the water consumption in terms of season and number of residents in households, (3) to calculate liters per capita day (LPCD) in terms of number of residents in households, and finally (4) to evaluate water savings by comparing water consumption of 80 pilot households with AMR systems to that of 100 control households without AMR systems.

2. Configuration of waterworks AMR systems in Republic of Korea

Waterworks AMR systems generally consist of several components: water meter/sensors, meter interface unit (MIU) to transmit detected data (flow rate, water quality, temperature, etc.) to data concentration unit (DCU), and communications network (neighborhood area network and wide area network) to transmit data from the specified unit to integrated server (see Fig. 1). The methods that transmit data to DCUs and to integrated server can be divided into three types: wire communication (power line communication, Internet networks, phones, cable TV networks, etc.), neighborhood area network (Zigbee, Bluetooth, etc.), and wide area network (CDMA, SMS paging network, satellite communication, etc.) [5,9,12,16,19–22].

Before waterworks AMR systems have been adopted in 2002, manual reading of mechanical accumulation water meters by a data collector was very common in Republic of Korea. Since 2002, images of the dial in mechanical accumulation water meters have been transmitted by using the image reading method with cameras, and data collection methods have been diversified into various communication networks suitable for local characteristics [21,22].

Recently, various types of smart water meters have been developed with ancillary devices (e.g. anti-freezing sensor, acoustic sensor, remote valves, and display units) [2,5,9,20–22]. Through various demonstrations and pilot projects, most of waterworks AMR systems in Republic of Korea transmitted data to DCUs with the reed switch type of smart water meters via RF (424 MHz, 10 mW) and Zigbee communication (2.4 GHz, 25 mW) methods, and transmitted data to the integrated server via the CDMA/power line communication methods [21,22].

Fig. 1. General waterworks AMR systems.

3. Experiment methods and field application

3.1. Smart water meter

As shown in Fig. 2, the 15 mm-diameter smart water meter developed in this study is the multi-jet meter that allows water flow into multiple ports inside the internal chamber. The water flowing into the chamber rotates the impeller with a magnet, and then the generated magnetic field is detected by the magneto-resistance sensor. The detected values of magnetic field are transmitted to pulse encoders to calculate the water flow. This magneto-resistance method has been reported to have high levels of accuracy and wide measurement span [5,21,22].

The precision of measured data has been verified via flow tests before smart water meters were installed in pilot test beds. Quality assurance (QA) was executed to test smart water meters operating within allowed error ranges according to various flow rates [i.e. the minimum flow ($Q_1 = 0.016\ m^3/hr$), transfer flow ($Q_2 = 0.1\ m^3/hr$), and the maximum flow ($Q_3 = 1.6\ m^3/hr$)]. All smart water meters evaluated in this study were confirmed to pass QA. Several characteristics of smart water meters developed in this study are summarized in Table 1.

Table 1
Characteristics of smart water meter developed in this study

Contents		Characteristics
Certification standard		Accepted
Size	Length (L)	165 mm
	Width (W)	92 mm
	Height (H)	97 mm
Performance after thaw		Accepted
Minimum flow rate		16 L/h
Maximum flow rate		1,600 L/h
Indicator	Minimum	0.1 L
	Maximum	9,999 m^3
Type of connected thread		PF 3/4′′

3.2. Waterworks AMR systems and pilot test beds

Control test beds composed of 100 control households used the conventional mechanical water meters, and manual reading of mechanical water meters was monthly performed by a data collector at the end of each month. Meanwhile, pilot test beds were prepared by replacing previous mechanical

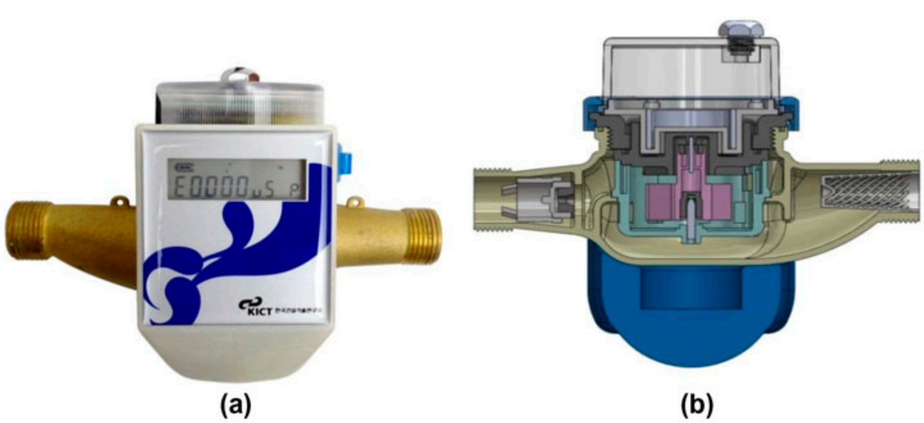

Fig. 2. Smart water meter developed in this study: (a) pictorial view and (b) cross-sectional view.

water meters with smart water meters developed in this study. Also, the information related to household water consumption, consumption patterns, and real-time bills was provided to 80 households in the apartment complex located in B-gu, Incheon City.

As shown in Fig. 3, the smart water meter data were transmitted from residents' homes to a wireless gateway over UHF, and the data were transmitted to integrated server through wire Internet or wireless Wibro communication. The data were monitored every 30 min, transmitted hourly, and stored at the integrated server in the management center. The maximum radius of wireless communication of smart water meter was limited to within 100 m from the DCU in consideration of low power consumption. The configurations of waterworks AMR systems applied in pilot test beds are summarized in both Table 2 and Fig. 3.

4. Results and discussion

4.1. Analysis of reception rate

Field performance tests of AMR systems were conducted from January to December in 2011. The monthly average reception rates of the monitored data were in the range of 74.7–99.1%, and the yearly average reception rates were 94.1%, which was relatively low as displayed in Fig. 4. In the beginning of installation (i.e. January), the reception rate was quite low (74.4%) due to network problems. Therefore, monitored data using smart water meters were not successfully transmitted to UHF receivers (see Fig. 3). After the problems in communication networks were fixed, the reception rate was significantly improved up to 91.5%, and did not show any remarkable change throughout the whole year. Consequently, poor reception rate according to changes in the external environment (e.g. high temperature and humidity in summer, low temperature and burst in winter) does not need to be considered in waterworks AMR installed in this study.

Nonetheless, the reception rate was not close to 100% for several reasons. For multiple-to-one communication with RF UHF, DCU, and Wibro, lower reception rate was caused by several problems such as low power supply, unstable Wibro networks within the specified time, shadow zones caused by meter protection boxes and installation environments, and temporary errors of routers. For one-to-one communication with RF UHF and Internet, monitored data were not normally received since some households disconnected receivers in January. After residents involved in pilot test beds were educated not to disconnect RF UHF receivers, the reception rate was close to 100% for one-to-one communication.

Therefore, in this study, one-to-one communication with RF UHF and Internet (i.e. TCP/IP) was found to

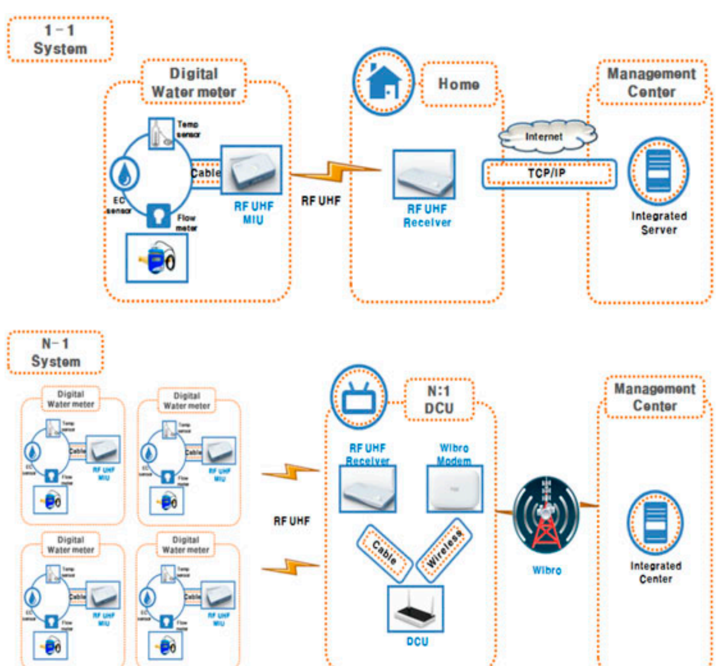

Fig. 3. Waterworks AMR systems adopted in this study.

Table 2
Characteristics of waterworks AMR systems adopted in this study

Contents	Method	Characteristics
Type of quantity sensing	Magneto-resistance Type	Sensing pulse generating circuit using magneto-resistance sensor
Meter interface unit (MIU)	Inside water meter box cover	Less concerns related to artificial damages Shorter communication distance
Neighborhood area network (NAN)	UHF 424 MHz	Excellent directional and overcoming against wall (compared to Zigbee & Bluetooth)
Wide area network (WAN)	LAN (1:1)	Connected via Internet LAN (TCP/IP)
	UHF-DCU-Wibro network (multiple:1)	Connected via wireless UHF & Wibro

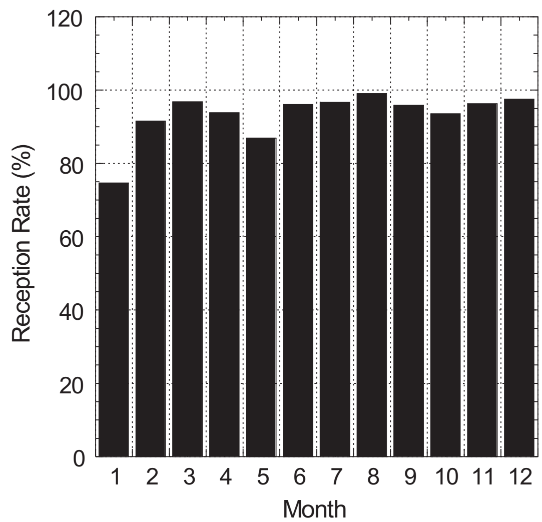

Fig. 4. Monthly changes in reception rate of waterworks AMR systems.

be more stable in AMR systems than multiple-to-one communication with RF UHF, DCU, and Wibro. Since accumulated monitored data were transmitted next time after communication failure occurred, there was no discrepancy in water bills. However, the optimization of communication networks in AMR systems is required to prevent meter reading errors and to ensure information tasks of both water consumption and bills.

The yearly average reception rates of each building in same apartment complex were also analyzed as shown in Fig. 5. The yearly average reception rates of the monitored data in each building were in the range of 87.1–98.5%, whereas the yearly average reception rate of 104 building was 87.1%, those of other buildings in same apartment complex were greater than 96.1%. The reason why buildings in the same apartment complex showed different reception rates was attributed to the facts that communication within specified time failed because of the shadow zones caused by meter protection boxes and different installation environments. Thus, communication networks including installation environments of smart water meter, neighborhood area network, wide area network, and network topologies were found to be significant to secure information tasks of both water consumption and bills.

4.2. Analysis of household water consumptions

The household water consumptions from field performance tests of AMR systems were analyzed. Both consumption amounts and patterns of the household water have been reported to be dependent on various factors (i.e. the number, age, occupation, and lifestyle of resident, type and area of building, size and function of city, weather, etc.) [5,7,9,12–17,21–26].

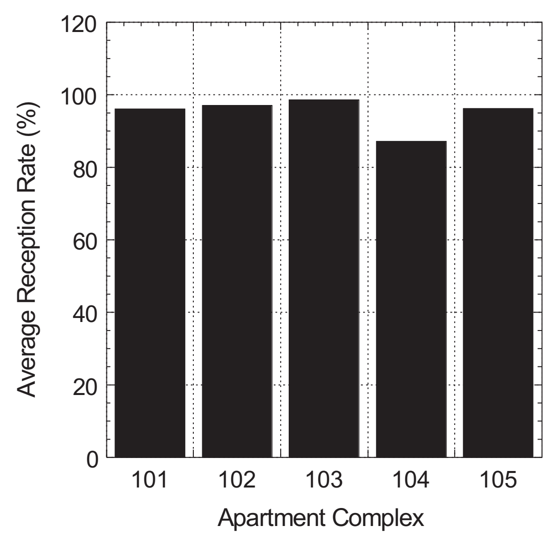

Fig. 5. Changes in reception rate of waterworks AMR systems for each building in the same apartment complex.

Generally, the major consumptions of household water in Republic of Korea can be classified into cooking, dish washing, bathtub, toilet flushing, and cloth washing, and the ratio of household water consumptions for each usage has been found to be dependent on social and cultural customs based on end-use analysis [21–26]. Among households that participated in field performance tests, a total of 80 representative households consisting of 1–5 residents by stratified random sampling were selected, and their average daily water consumptions were analyzed as shown in Fig. 6. As shown in Fig. 6(a), households with more residents consumed more water than those with fewer residents.

For all households, water consumption increased gradually from January, was the maximum in August, and then decreased gradually to December. Through the trend line obtained via the regression using Stineman function, the consumption of household water clearly showed seasonal periodicity. These results were attributed to the weather factors in the seasons (e.g. temperature, humidity, activity of human being, etc.) that affected the water consumption, and were consistent with those of the previous study that have reported seasonal periodicity of household water consumption [21–23,26].

4.3. Analysis of LPCD

LPCD is an index that generally represents water consumption by single person for one day. Using this index, the changes in the household water consumption have been compared by country, city, house, year, season, and characteristics of residents [7,9,21–26]. By comparing the LPCD values, the changes in water consumption have been found to be dependent on the area and type of houses, the number, age, income, and occupation of residents, pressure, temperature, and quality of water supply [7,9,21–26].

In this study, the LPCD values of 80 households were analyzed in terms of number of residents, and the trend line was obtained via the regression using Stineman function, as shown in Fig. 7. Similar to the total amount of household water consumption shown in Fig. 6, LPCD values obviously showed seasonal periodicity, and the fewer number of residents (one or two residents) displayed more distinct seasonal periodicity. However, as the number of residents increased, the LPCD values gradually decreased and displayed similar seasonal periodicity. Similar results have been reported from the previous study [21,23,26]. Although the detailed consumptions of household water including toilet flushing, washing, cooking, cleaning, etc. were not directly monitored, the LPCD values were found to decrease gradually as the number of residents increased. These results were due to the saving effects through common consumption (i.e. toilet flushing, washing, cooking, cleaning, irrigation, etc.) in the case when many residents live in the same household, although common consumption was still required in the case even when a single resident lives in a household.

As it is evident from Table 3, which summarizes the analysis results of LPCD values for 80 households, the LPCD was the maximum value (252.3 L/p/d) in the case where a single resident lives in a household. As the number of residents increased, the LPCD values gradually decreased and reached the minimum value (148.5 L/p/d) in the case where five residents live in a household, regardless of installation environments. On an average, the LPCD values decreased by about 20.8 L as the number of residents increased by one. Consistent with this study, the LPCD values were reported to decrease by 10–25 L as the number of residents increased by one [21,23,26].

The average LPCD of 80 households investigated in this study was 204.8 L/p/d, which was greater than that (i.e. 195 L/p/d) for households living in apartments in Seoul during 2003 [23,26]. Also, the average LPCD estimated from this study was greater than that (i.e. 183–188 L/p/d) for households in 16 cities in Chungnam Province from 2002 to 2006 [23]. These results stemmed from the fact that households in more urbanized cities used more water than less urbanized cities, despite living in the same type of housings (i.e. apartment complex) [23,26]. Furthermore, the water consumptions significantly increased in 2011, compared to those in 2003. Thus, when water supply plans are prepared, different LPCD values according to the scale of cities, housing types (e.g. apartments, detached houses, and tenement houses), regions, and future demand should be considered.

Although the detailed consumptions of household water were not identified in this study, water consumptions per capita day were successfully obtained by smart water meters with waterworks AMR systems. Since real-time water consumption and trend analysis are available through online presentation of consumption data for all households, there is significant potential for demand reduction as a behavior response to increased information.

4.4. Evaluation of water savings

Although both real-time water consumption and trend analysis were provided to all households engaged in pilot test beds through a web portal, there were only limited accesses to the web portal to moni-

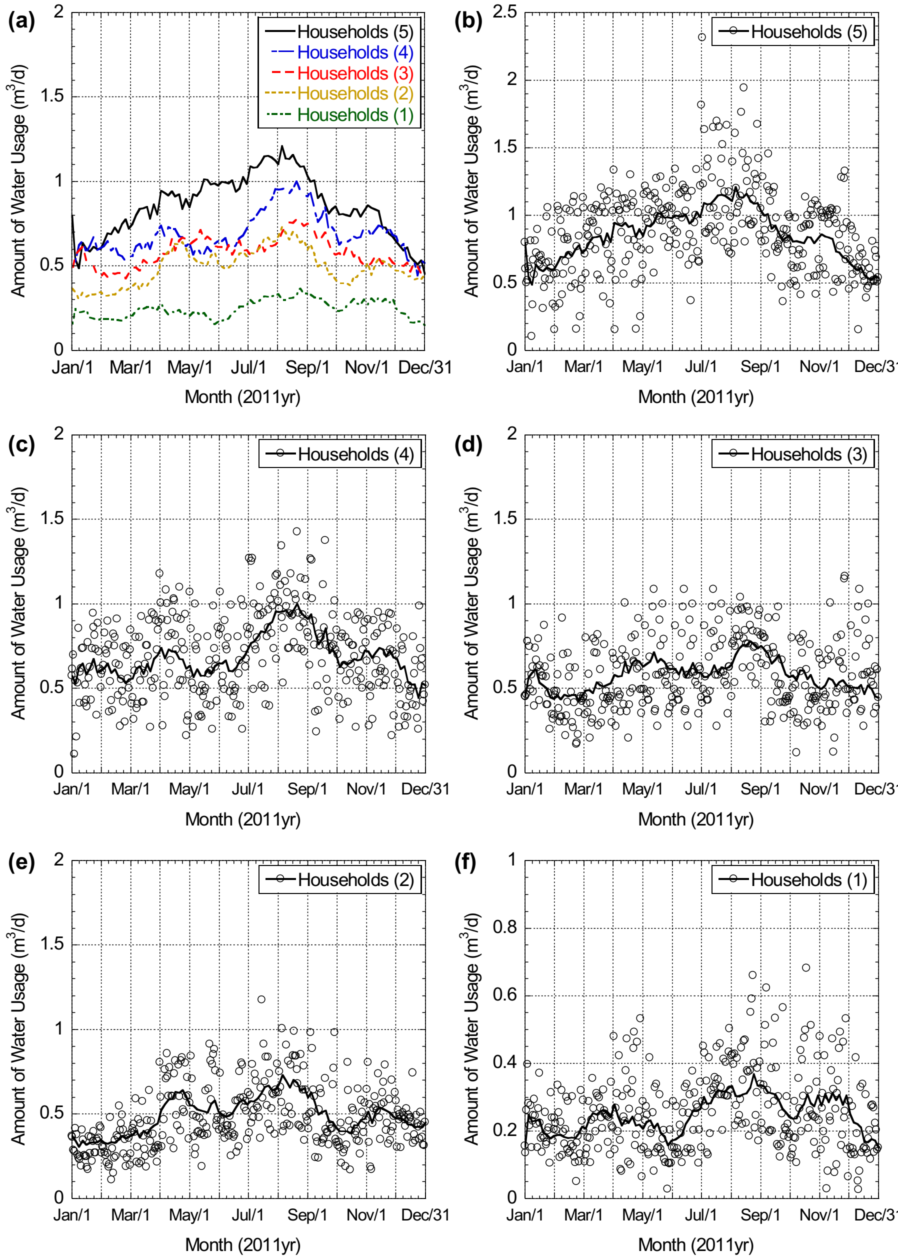

Fig. 6. Time series plot of water consumption in terms of the number of residents in a household (note that open circle indicates daily water consumption; solid line indicates trend line using Stineman function).

tor the water consumption on an hourly and daily basis. Mostly, some residents monitored their cumulative water consumption and bills at the end of month in the initial period of pilot test beds. In order to evaluate water savings by adopting waterworks AMR systems, the water consumption of 80 pilot households with AMR systems were compared with that of 100 control households with conventional mechanical water meters. Based on the manual meter reading data from control test beds with 1–5 residents, the difference of LPCD values between pilot test beds and control test beds was calculated in terms of number of residents.

As shown in Fig. 8, the average LPCD values of 80 pilot households were reduced by 5.3%, relative to those of 100 control households. These results may be partially attributed to the various web portal functions that displayed the water consumptions and water bills, and the changes in awareness and behavior of water consumptions lead to water savings. Consistent

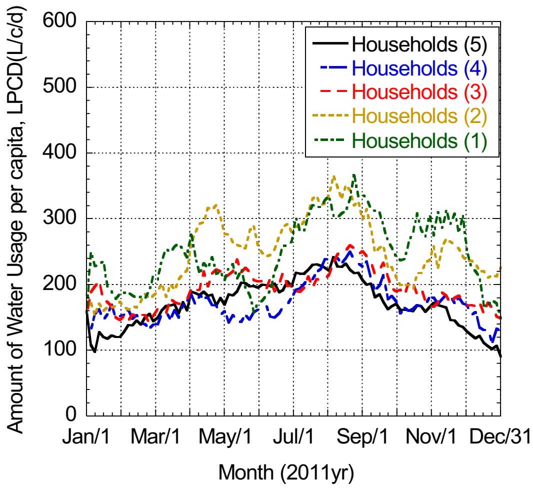

Fig. 7. Time series plot of water consumption per capita day in terms of the number of residents in a household (note that dotted line indicates trend line using Stineman function).

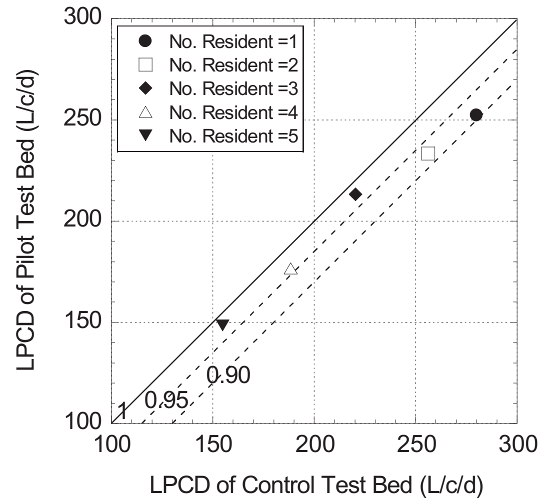

Fig. 8. Comparison of the average LPCD values between 80 pilot households and 100 control households in terms of the number of residents in a household.

Table 3
Values of water consumption (LPCD) based on the number of residents in a household

No. of residents	1	2	3	4	5
101 house	253.1	242.7	215.2	177.1	171.2
102 house	264.3	220.8	204.1	184.2	133.5
103 house	268.1	261.2	231.7	197.9	148.2
104 house	231.5	218.5	213.8	168.6	151.0
105 house	244.4	223.6	201.5	156.0	138.4
Average	252.3	233.4	213.3	176.8	148.5
Total average	204.8				

with this study, Doolan [17] reported that water consumptions were estimated at an average reduction of 7–10% after an 18-month smart water metering residential project in Sydney (Australia), and Milind [9] also stated that water pilot households in city of Dubuque (USA) reduced water consumption the most by 10%, compared to the control group of households with no portal access.

As also shown in Fig. 8, the difference of LPCD values between pilot test beds and control test beds increased as the number of residents decreased. This result may be due to cultural variables that many residents living in the same household cannot save water together without education and participation, whereas one or two residents can save water simply by reducing common consumptions (i.e. toilet flushing, washing, cooking, cleaning, irrigation, etc.). Also, water bills based on water consumption do not encourage the residents to save water due to the very low price of water in Republic of Korea. These results also indicate that the deployment of developed waterworks AMR systems needs to include the broader social, cultural, and emotional variables towards more sustainable water use. Consequently, the deployment of developed waterworks AMR systems integrating smart water metering, end-use water consumptions, communication networks, and real-time information should be encouraged to conserve both water and energy for smarter cities.

5. Conclusions

The 15 mm-diameter smart water meter was developed and waterworks AMR systems with 15-mm diameter smart water meters were installed in 80 households out of 320 households in the apartment complex located in B-gu, Incheon City. Then, real-time information on both water consumption and patterns of household water consumption through waterworks AMR systems was analyzed. The monthly average reception rate of the monitored data was in the range of 74.7–99.1%, and the yearly average reception rate was 94.1%. The one-to-one communication with RF UHF and Internet (i.e. TCP/IP) was found to be more stable in AMR systems than multiple-to-one communication with RF UHF, DCU, and Wibro. Also, the yearly average reception rate of the monitored data in each building was in the range of 87.1–98.5%, depending on different installation environments. Thus, communication networks including installation environments of smart water meter, neighborhood area network, wide area network, and network topologies were found to be significant to secure information tasks of both water consumption and bills.

For all households, water consumption increased gradually from January, was the maximum in August, and then decreased gradually, showing seasonal periodicity due to the weather factors in the seasons (e.g. temperature, humidity, activity of human being, etc.). Also, as the number of residents increased, the LPCD gradually decreased and displayed similar seasonal periodicity. These results were due to the saving effects through common consumptions (i.e. toilet flushing, washing, cooking, cleaning, etc.). On average, the LPCD decreased by about 20.8 L as the number of residents increased by one. The average LPCD values of 80 pilot households were reduced by 5.3%, relative to those of 100 control households. These results may be partially attributed to the various web portal functions that displayed the water consumptions and water bills, and the changes in awareness and behavior of water consumptions lead to water savings. Finally, the deployment of developed waterworks AMR systems integrating smart water metering, end-use water consumptions, communication networks and real-time information should be encouraged to conserve both water and energy for smarter cities.

Acknowledgement

This study was supported by the major project (2013-0015) of the Korea Institute of Construction Technology.

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